Modelling of fibre-optic DAS response to microseismic arrivals in anisotropic media

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Summary

Fibre-optic Distributed Acoustic Sensing (DAS) cables are now used to monitor microseismicity during hydraulic fracture stimulations of unconventional gas reservoirs. Unlike geophone arrays, DAS systems are sensitive to uniaxial strain along the fibre direction and thus provide a single-component recording, which makes identifying the directionality of incoming waves difficult to infer. Using synthetic examples, we show some fundamental characteristics of microseismic recordings on DAS systems for purposes of hydraulic fracture monitoring in a horizontal well in anisotropic (VTI) shales. We demonstrate that SH arrivals dominate the recorded signals since their polarization is aligned along the horizontal cable at near offset. The amplitude of the SH phase along the cable exhibits a characteristic pattern with bimodal peaks, the width of which relates to the distance of the event from the cable. Furthermore, we find that shear-wave splitting recorded on DAS systems can be used to infer the inclination of the incoming waves, overcoming a current limitation of event locations which have constrained events to lie in a horizontal plane. Low amplitude qSV arrivals suggest an event depth similar to that of the DAS cable. Conversely, steep arrivals produce higher amplitude qSV waves, with shear-wave splitting increasing with offset along the cable.

Introduction

In the last decade fibre-optic technology has developed to use distributed acoustic sensing (DAS) cables to measure the dynamic strain induced by seismic waves (Parker et al., 2014). This new technology is now being deployed for the microseismic monitoring of industrial activities such as hydraulic fracturing and CO_2 geological storage. The technology has many advantages, such as broadband dense spatial sampling since the fibre provides a continuous line of sensors, often with thousands of channels. Unlike conventional seismic sensors, DAS systems are sensitive to the uniaxial strain along the direction of the fiber optic cable. As a result, the systems provide a single component recording polarized in the cable direction rather than the standard three components provided by geophones. Such differences may lead to an ambiguity in the directionality of incoming waves, and some of the patterns observed may run counter to intuition for those more familiar with geophone recordings. Here we use synthetic examples investigate some fundamental characteristics of microseismic data recorded on DAS systems for the purposes of hydraulic fracture monitoring in anisotropic shales.

Synthetic modelling

We design our model based on a real microseismic dataset recorded during a single stage of a hydraulic fracturing stimulation in a horizontal well. The stimulation occurred in an adjacent horizontal well, thus we expect most of the ray paths to be nearly horizontal, but with some events spread out above and below the well, and within a few hundred metres of the monitoring well. We choose a homogeneous VTI velocity model based on cross-dipole sonic logs (V_{P0} = 2800 m/s, V_{S0} = 1750 m/s, $\boldsymbol{\varepsilon}$ = 0.42, $\boldsymbol{\gamma}$ = 0.36, $\boldsymbol{\delta}$ = 0.21).

To create the DAS synthetics, we first model the velocity wavefield using the 3D finite-difference wave propagation code SAVA (Köhn et al., 2015). We sample the wavefield along an array of 500 receivers at one metre spacing (equal to the channel spacing of the DAS cable). The conversion from velocity to DAS synthetics is summarised in Figure 1.

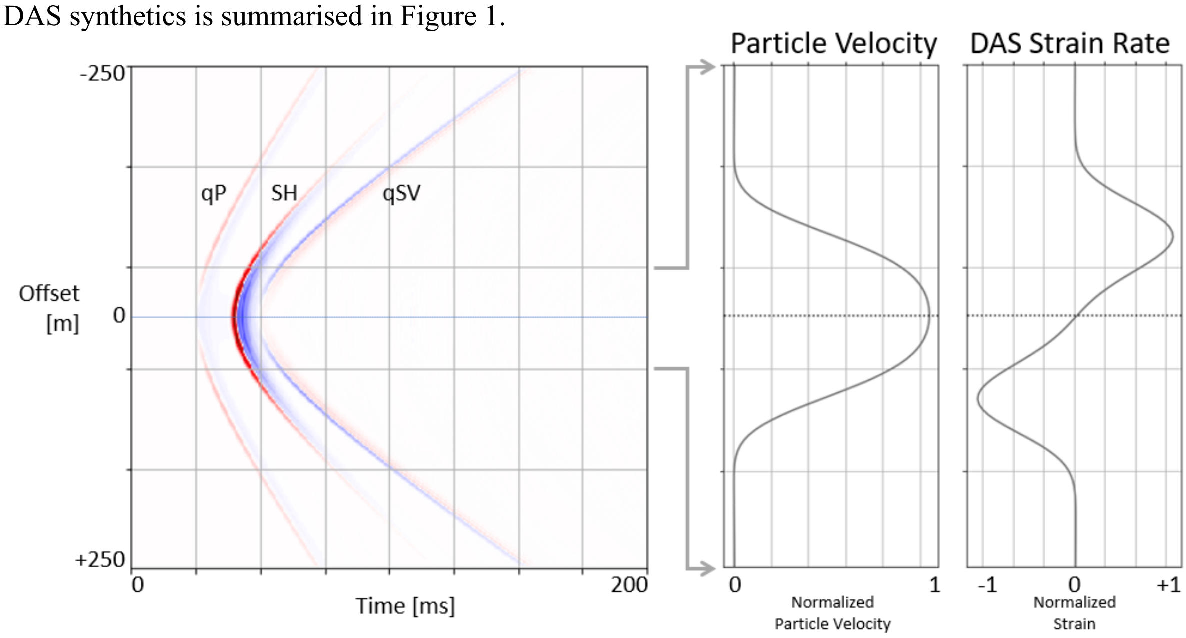

Figure 1 *Modelled particle velocity along the horizontal well direction for a microseismic source in a homogeneous VTI medium (left). Snapshots of the particle velocity (right, labelled Particle Velocity) and strain rate (right, labelled DAS Strain Rate) along the fibre at the peak amplitude of SH arrival. Since strain rate is the spatial derivative of particle velocity along the fibre the peak amplitude for particle velocity translates to zero amplitude in DAS data.*

First, we take only the component of the velocity wavefields polarized in the direction of the DAS cable (Fig. 1, left). We note that for a horizontal array in a VTI medium the qP and qSV velocity amplitudes vanish at zero offset (~0 m) because these phases are polarized perpendicular to the fibre. Conversely the SH phase is polarized along the fibre producing a strong signal with peak velocity amplitude at zero-offset. To convert the particle motion to DAS strain-rate synthetics we take the spatial gradient of the particle velocity along the fibre measured over a fixed length typically referred to as the 'gauge length', which in our case is 10 m. An interesting consequence of this is that the peak SH amplitude in the particle velocities translates to zero amplitude when converted to DAS strain-rate (Fig. 2).

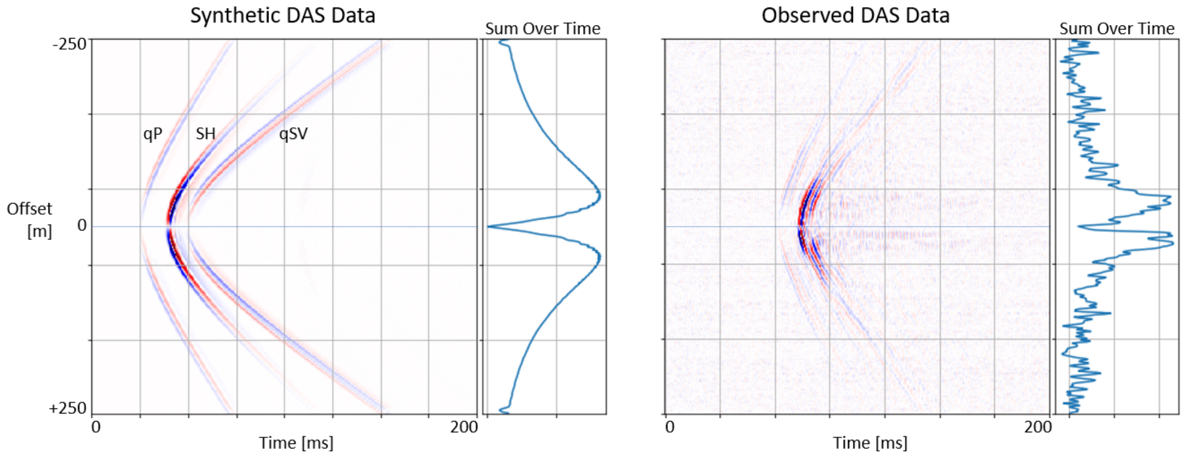

Figure 2 *Synthetic DAS data (left) along a horizontal well for a microseismic source in a homogeneous VTI medium. Waveforms to the right show observed DAS data. Plots to the rights of the waveforms show the sum of absolute amplitudes over time.*

This results in an interesting observed pattern in the DAS signal. Like the velocity data the strongest signal is contained in the SH phase; however, it is no longer centred at zero-offset. Instead, there is a bimodal amplitude pattern with a local minimum at the zero-offset point to the fibre (Fig. 2, left). This pattern closely matches those observed in real data (Fig. 2, right).

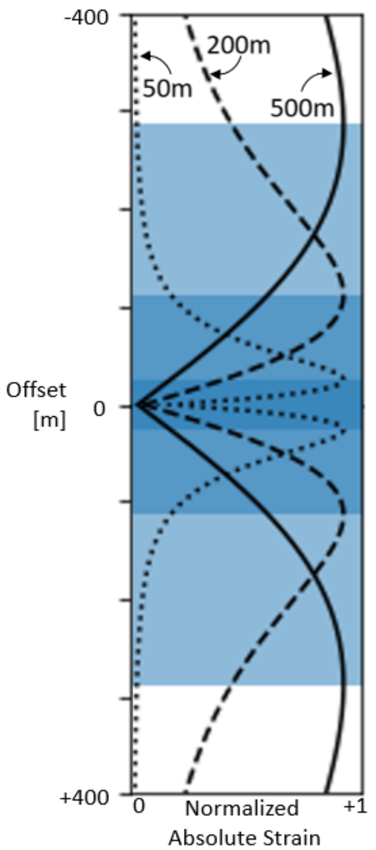

Figure 3 *(left) Predicted axial SH strain as a function of fibre offset for sources of uniform radiation pattern with varying distances from the fibre within the horizontal plane. The blue rectangles indicate the separation along the cable between the bimodal amplitude peaks, which is proportional to the distance to the source.*

This bimodal amplitude pattern may provide useful insight into constraining the source location. Figure 3 shows axial strain along the fibre for SH arrivals modelled using ray-tracing for events located in the horizontal plane at 50 m, 200 m and 500 m from the cable. A uniform radiation pattern is used, and the modelled amplitudes include geometrical spreading. It is clear that the separation between the amplitude peaks is proportional to the distance of the event from the cable. In practice, the relationship may be more complex due to non-uniform radiation patterns as well as arrivals from steeper inclinations in an anisotropic VTI medium; nevertheless, the separation of amplitude peaks provides a first-order estimate of event distance.

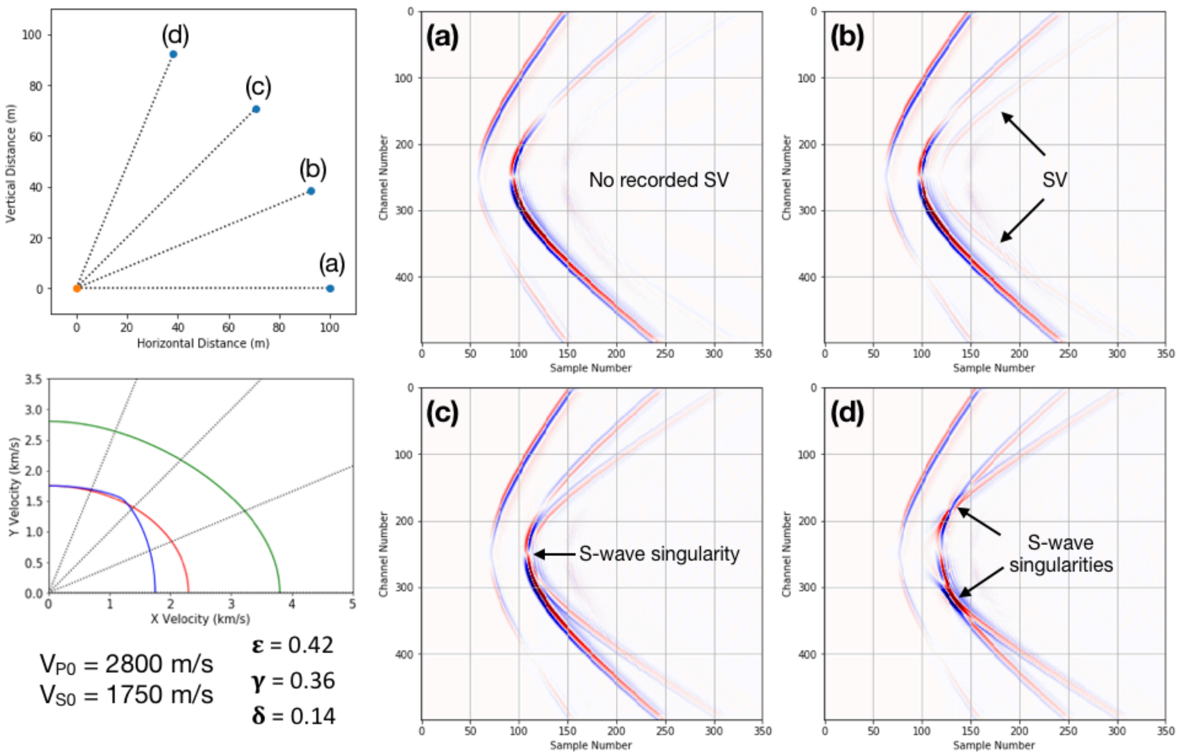

Figure 4 *Synthetic DAS data for events located 100 m from the horizontal cable in a VTI medium at progressively steeper inclinations from horizontal. Top left panel shows the 4 source locations (blue circles, labelled a to d) distributed around the fibre (orange circle). The bottom left panel shows the model's qP (green line), qSV (blue line) and SH (red line) group velocities as a function of ray inclination.*

We now investigate the use of shear wave splitting to help constrain event depths relative to the cable. We model four sources at a fixed distance of 100 m from the cable with increasing inclinations of 0°, 22.5° ,45°, and 67.5° measured from the horizontal plane. For the 0° event located within the horizontal plane (Fig. 4), we might expect to observe significant shear-wave splitting based on the model's Thomsen parameters. However, since the ray-paths from the source to the fibre are horizontal, the qSV phase is polarized in the vertical direction and does not generate any axial strain along the horizontal cable and is not observed in the DAS data. As inclination is steepened the qSV arrivals progressively project a larger horizontal component and generate axial strain along the fiber and hence will be observed on DAS recording (Fig. 4). For this anisotropic model the difference the SH and qSV velocities decrease for steeper inclinations towards zero around 45° where there is a S-wave singularity and the two shear waves propagate with the same velocity. Figure 3c shows this singularity at zero offset where there is no observed shear wave splitting. Splitting is observed, however, at larger offsets since inclination shallows as you move along the cable, resulting in an increase in apparent shear wave splitting with distance. For steeper inclinations the qSV arrival becomes the first S arrival observed at near offset and the moveout of the qSV and SH phases cross showing two S-wave singularities. The presence of S-wave singularities is model dependent and is controlled by the relative magnitudes of the Thomsen parameters. Nonetheless, if such singularities are observed it is a strong indicator of a steep incidence angle. This effect has been observed in the field data (see Figure 5) which is compared to a modelled event showing S-wave singularities in DAS data.

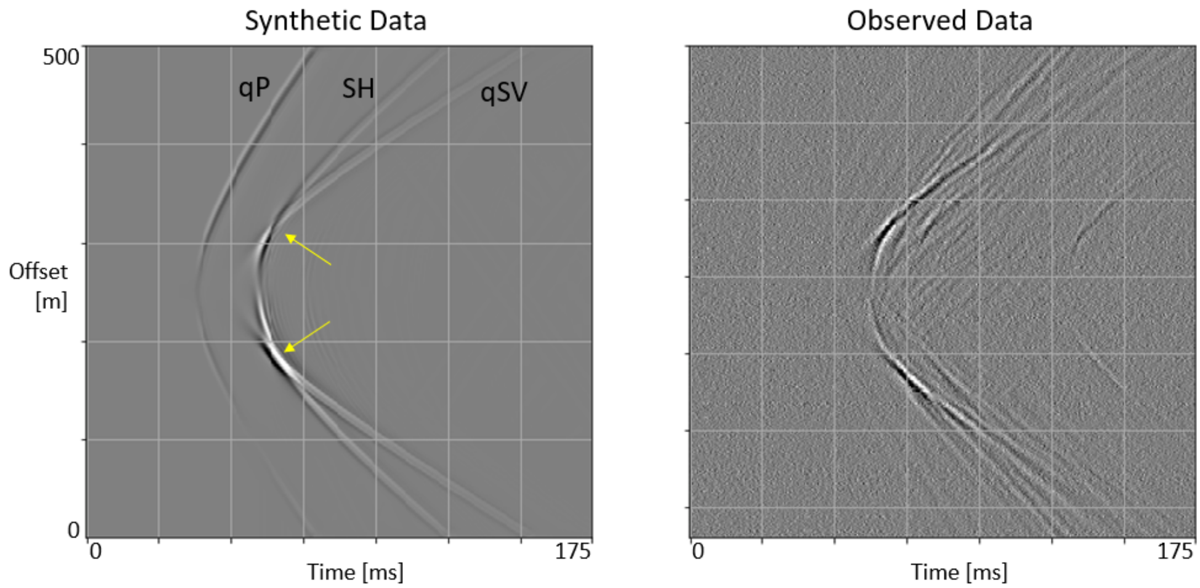

Figure 5 *Synthetic DAS recording (left) of an event showing S-wave singularities (indicated by yellow arrows) compared with a real example (right) showing a similar feature. The observance of S-wave singularities is a strong indicator of a steep incident angle.*

Conclusions

Through full waveform synthetic wavefields we have explored some fundamental characteristics of microseismic data recorded on horizontal DAS arrays in VTI media, which may aid in constraining event locations and reducing ambiguity in the directionality of waves. We have demonstrated that the SH phase usually dominates the signal due to its polarization along the cable at near offsets. The amplitude of the SH phase along the cable produces a characteristic pattern with bimodal peaks surrounding the zero-offset point, with the separation between the peaks providing an indication of the distance of the event from the cable. Insight into the depth of an event relative to the cable can be gained by observing characteristics of the shear-wave splitting. For events in the horizontal plane the qSV phase will not be recorded because of its polarization perpendicular to the fibre. For events above or below the horizontal plane the qSV phase can be observed and the details of shear wave splitting and how it changes with offset along the cable can provide insight into the near offset inclination. The observance of S-wave singularities, for example, provides a strong indication for a steep arrival. Using these features in VTI media can reduce some of the uncertainty of the directionality of waves inherent in using single component data.

Acknowledgements

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References

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